# Literature review of airflow fluid characteristics and their impact on human thermal comfort

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**Abstract:** Airflow dynamics significantly impact indoor thermal environment and human thermal comfort. Studies on the effects of airflow fluctuations on thermal comfort mainly focus on the effects of turbulence intensity and fluctuation frequency. The fluctuant characteristics of natural wind and mechanical wind are obviously different. However, the fluctuant characteristics of mechanical wind can shift to those of natural wind in some conditions. With the development of turbulence statistical theory, chaos and fractal theory, researchers began to use these theories to describe the structural characteristics of the fluctuating airflow in different environments or by different generating sources. The results of studies on airflow fluctuation and thermal environment are reviewed in this paper from two aspects: 1) the effect of the airflow fluctuations on thermal comfort, and 2) the physical structure of airflow fluctuations. This paper first reviews these achievements, and then summarizes studies conducted at Tsinghua University.

**Key words**: dynamic characteristics of airflow; natural wind; mechanical wind; power spectrum; thermal comfort

## 1. INTRODUCTION

A steady thermal environment is the goal of the conventional building thermal environment control, which is characterized as neutral thermal sensation, combined with the limitation of airflow velocity lower than 0.15m/s and the relative humidity around 50%. However, in practical applications, the steady thermal environment may cause two main problems: "air-conditioning syndrome" due to the lack of environment stimulus and high energy cost caused by keeping constant low air temperature for human thermal comfort.

Investigation indicates that people have good adaptability to the environment among natural ventilated building [1-3, 13]. Based on this conclusion, if passive or mechanical method can be used to create a stimulating natural environment in building space, environment suited for human physiological health can be obtained as well as high energy cost can be reduced. Meanwhile, the problems caused by the traditional steady method, such as decline of human temperature adjustment function and resistance, can be avoided..

The problem of the steady thermal environment and the advantage of naturally-ventilated environment impel the change of the emphasis of study from steady parameters to dynamic properties, among which dynamic flow attracts most attentions. The studies on the effect of airflow fluctuation in built environments are reviewed in this paper as two topics: the effect of airflow fluctuation on human thermal comfort and the physical structure of airflow fluctuation. The review is focued on the research work performed in Tsinghua University.

## 2. EFFECT OF DYNAMIC CHARACTERISTICS OF AIRFLOW ON THERMAL COMFORT

Since 1920s, American researchers began to study the effect of airflow fluctuation on thermal comfort. In the early studies, mean velocity was considered as the main parameter. However, further studies indicated that it was not adequate to use only the mean velocity to evaluate the effect of airflow on thermal comfort[25], and then the periodically fluctuant airflow was studied and the fluctuant parameters such as turbulence intensity and fluctuant frequency were analyzed to find the relationship between fluctuant characteristics of airflow and human responses.

### 2.1 Effect of Turbulence Intensity

A mass of experimental studies were carried out to investigate the relationship between airflow turbulence intensity and thermal comfort and they are falling into two main categories. One is to study the effect of air turbulence intensity on the percentage of dissatisfied with draught according to the subjects' vote on acceptability under different air turbulence intensities from the viewpoints of physiology and psychology [4,5,28]. The other is to study the effect of turbulence intensity on the convective coefficient from the viewpoint of heat transfer [6,28]. From the above research results, it has been widely accepted that the dissatisfaction due to draught increased with the increment of turbulence intensity. This conclusion is mainly drawn from two different aspects: one is to believe that the convective heat transfer coefficient will increase with the increment of turbulence intensity and thus the heat flux from skin will be enhanced; the other is to believe that the increase of turbulence intensity causes the fluctuations of skin temperature. In the environment with high air turbulence intensity, the fluctuant rate of skin temperature becomes so fast that human body may send alarm signal to brain and cause the feeling of draught. [7].

2.2 Effect of Fluctuation Frequency

According to the turbulence theory, the basic characteristic of turbulence is that the turbulent flow consists of a mass of eddies of different scales. Different eddies have different fluctuant cycles and frequencies. In 1977, Fanger and Pedenson et al.[8] studied the effect of periodically fluctuant airflow on human thermal sensation. The results showed that both frequency and amplitude of air speed were important factors to influence thermal comfort and the airflow at the frequency range of 0.3-0.5Hz is the most sensitive to cause draught. In 2000, Xia[9] systematically studied the influence of turbulence intensity and frequency of fluctuant airflow on thermal comfort and found that frequency of fluctuant airflow was also an important factor and the airflow with the frequency range of 0.3-0.5Hz would produce the strongest cooling effect. Arens et al. [10] carried out the experiments on two groups of airflow with the same average velocity and different fluctuant frequencies, and found that the airflow at the frequency range of 0.7-1.0Hz had more cooling effect. At the same time, some other researchers developed simulation models for the response of human skin thermoreceptors to study the effect of fluctuation frequency on thermal sensation [9,11].

2.3 Effect of Other Fluctuation Parameters

Besides above fluctuation parameters, power spectrum intensity drawn from turbulence power spectrum analysis is considered by some researchers a very important parameter influencing thermal comfort [12]. In 2000, Jia [13] found that the power spectrum of airflow generated by a fan which motor's rotating speed was controlled by chaos signal had the same fluctuant characteristics with mechanical wind. He analyzed the different mechanisms of natural and mechanical wind and developed a method to utilize a rotational pan in the air supply terminal to change airflow distribution so that different airflow power spectrums could be generated. Such a dynamic air supply terminal could be used to generate the 'natural wind' which agreed with the four indexes of natural wind presented by Zhu [19]. Jia performed thermal comfort experiments with different airflow modes and indicated that the airflow of which the spectrum was close to the natural wind was perceived more pleasant by subjects than others (constant airflow, sinusoidal variation airflow and stochastic variation airflow).

## 3. PHYSICAL STRUCTURE OF AIRFLOW

The effect of airflow fluctuations on thermal comfort promotes the studies on fluctuant characteristics of airflow. The development of turbulence statistical theory, chaos and fractal theory provide the method to describe the fluctuant characteristics of airflow. In 1980s, researchers from Denmark [14], Hong Kong [15] and Chinese mainland [12] respectively adopted stochastic analysis to study the turbulence characteristics of airflow in air-conditioned or mechanically ventilated rooms. The analytical parameters included turbulence intensity, standard deviation, turbulent integral scale and correlation. Since 1990s, Researchers in the Department of Building Science at Tsinghua University adopted several nonlinear indexes including phase space restructure map, information entropy and information dimension to analyze airflow fluctuant characteristics in different kinds of environment or different supply sources and have already achieved some valuable results.

3.1 Difference and Connection Between Natural Wind and Mechanical Wind

The Japanese researchers carried out studies to introduce the feature of natural wind into indoor environment. In 1980s, they found that the natural wind has the feature of $1/f$ fluctuations[16], and some of them adopted nonlinear research tools such as frequency analysis and phase space method to study the fluctuant characteristics of natural wind [17]. The $1/f$ fluctuations are ubiquitous in nature. The signal (or noise) in nature can be classified into three kinds (see Figure 1). A fluctuation or noise with constant power spectrum which is independent of the frequency (negative slope of logarithmic power spectrum curves $\beta$=0) is named white-noise; The noise with $\beta$ equal to 2 is named Brown noise, and the noise with $\beta$ value between 0 and 2 is named $1/f$ noise. The $1/f$ fluctuations are ubiquitous in nature and have close relationship with people's pleasure.[18]

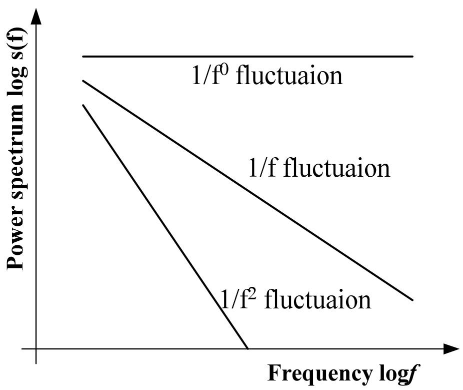



**Fig. 1 Power spectrum of typical fluctuations**

In 2000, Zhu[19]studied the difference between natural and mechanical wind. She made a large number of measurements and analysis of outdoor natural wind and mechanical wind, and proposed four indexes to distinguish natural wind and mechanical wind: 1) negative slope of logarithmic power spectrum curves $\beta$ (also called power spctrum exponent); 2) dimensionless width $\delta$ of phase space reconstruction map; 3) information entropy *Si*; 4) information dimension *Di*. She believed that $\beta$ is a key index to distinguish natural and mechanical wind and gave such a criterion: if $\beta$>1.1, it is judged to be natural wind; if $\beta$<1.1, it is judged to be mechanical wind. Phase space reconstruction is another important method to study the signal correlation. In analyzing the difference between natural wind and mechanical wind, the procedure of phase space reconstruction is the following: First, suppose the delay time is $\Delta\tau$, take the datum at time $\tau$ as *xi* and the datum at time $\tau+\Delta\tau$ as *yi*, then a curve of (*xi, yi*) for this data serial can be drawn in a two dimensional phase space. Figure 2 gives the typical maps of phase space reconstruction of natural wind, buoyancy air flow and mechanical wind. It can be found that there exist obvious differences in the shapes of phase space reconstruction maps among these three kinds of airflows.

Zhu defined a dimensionless width $\delta=B/L$ to describe the shapes of the phase space reconstruction maps (see Figure 3) and gave another criterion: if $\delta$<0.25, it is judged to be natural wind; if $\delta$>0.25，it is judged to be mechanical wind.

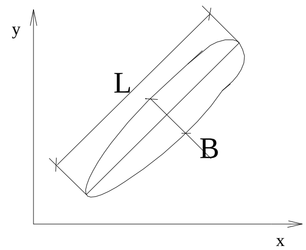
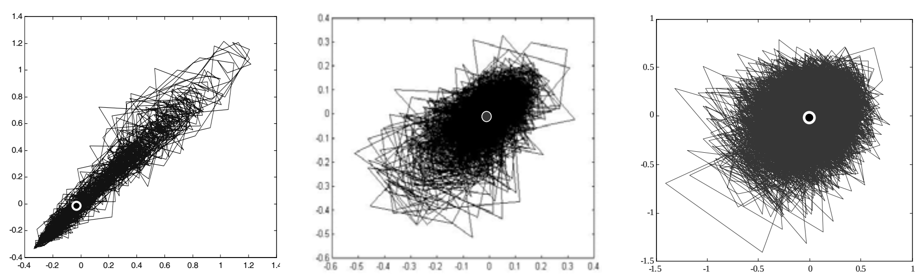



**Fig. 3 Definition of $\delta$ [19]**

Information entropy (*Si*) and information dimension (*Di*) are another two indexes presented by Zhu[19], which describe disorderness of the system structure[20]. Because the disorderness of mechanical wind is stronger than natural wind, both *Si* and *Di* of mechanical wind are greater than natural wind. Zhu regarded them as criterion indexes and gave the following criterion: if *Si*-0.2139*v*<3.45 or *Di*－0.0735*v*<1.6, it is judged to be natural wind; if *Si*-0.2139*v* >3.45 or *Di*－0.0735*v*>1.6，it is judged to be mechanical wind.



**Natural Wind** **Buoyancy Flow** **Mechanical Wind**

**Fig. 2 Phase space reconstruction curves of typical natural wind, buoyancy flow and mechanical wind [19,21]**

Zhu analyzed the outdoor natural wind and mechanical wind, while Tan[21] used nonlinear analysis tool to study the influence of opening and space of naturally-ventilated building on the fluctuant characteristics of natural wind. He found that $\beta$ value of outdoor natural wind near building was close to 1.1, while gradually increased to 1.7 when airflow entered into the indoor space because of the effect of door and window. The indoor airflow still had the *1/f* fluctuant characteristics but had the trend of the Brown noise.

Ouyang[26]carried out a large number of experiments to investigate the differences and connections between natural and mechanical wind and the rule of dynamic characteristics of airflow in the space. Based on the experimental results they proposed five indexes to distinguish natural wind and mechanical wind: 1) Probability distribution of the velocity, *Sk*; 2) Turbulence Intensity, *Tu*; 3) Negative slope of logarithmic power spectrum curves, $\beta$ ; 4) Turbulent integral scale, *L* and 5) Dimensionless spectrum characteristic index which describes the fractal characteristic of power spectrum *e* value .

Turbulence intensity (*Tu*) represents the relative magnitude of the velocity fluctuation over a time interval. Skewness (*Sk*) describes the differences between probability distribution of the velocity and the normal distribution. In addition, Ouyang [26] brought in *e* value as another index, which is used to describe the fractal characteristic of power spectrum. As to turbulence, when power spectrum density *E*(*f*) equals to f(-$\beta$), turbulence is into inertial range and have *1/f* fluctuant characteristics, *e* value can be defined by following equation:

$$e=\sqrt{\left(\frac{1}{N}\sum\left(\lg E_n(f)-\lg E(f)\right)^2\right)} \quad (1)$$

Where *f* is the frequency (Hz).

*E*(*f*) is the power spectrum density ($m^2/s$) which meets the following equation:

$$\int_0^\infty E(f)df=\overline{v'^2} \quad (2)$$

*En*(*f*) is the regression value of power spectrum density by least square method ($m^2/s$)

So *e* value is the regression error of least square method, and it can be used to estimate the fractal characteristics of logarithmic power spectrum curves. The smaller *e* value is, the more the logarithmic power spectrum curves assemble a line and the distinguished the degrees of fractal and *1/f* fluctuations become.

Besides, turbulent integral scale *L* has an intuitively physical sense and can accurately describe the fluctuant characteristics of airflow in built thermal environment. Thus, it can also be used as an important criterion to distinguish natural wind and mechanical wind.

Figure 4~figure 7 show the change of $\beta$ values, *L*, *Tu* and *Sk* of natural wind and mechanical wind with mean velocity. For natural wind, *Tu* is always larger than 60% and the probability distribution of the velocity is obviously skew distribution. Turbulence integral scale *L* is larger and the $\beta$ values keep at 1.5 or so when mean velocity is lower than 4 m/s. However, For mechanical wind, $\beta$ values vary greatly with the diffusing in space. *Tu* is smaller and the probability distribution of the velocity is normal distribution around the air supply opening, turbulence integral scale *L* is smaller (it is close to the scale of outlet) and the $\beta$ values distribute between 0~0.5 and are obviously less than the values of natural wind. With the diffusion of mechanical airflow in space, $\beta$ values increase while the mean velocity decreases gradually. When $\beta$ values of airflow reach the values of natural wind (1.4~1.7), the mean velocity decreases to 0.2 m/s. However, at this time the mean velocity has been in the scope of natural convection, and the effect on people is so limited that it can almost be ignored. So it can be concluded that in the airflow sensitive range for human response, the $\beta$ values of natural wind are different from the one of mechanical wind obviously, and the demarcation point is around1.2-1.3.

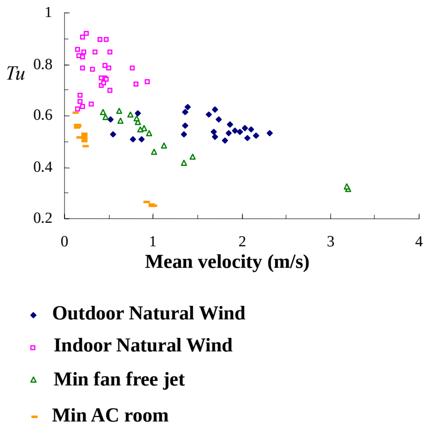



**Fig.4 *Tu* values of natural and mechanical wind[26]**

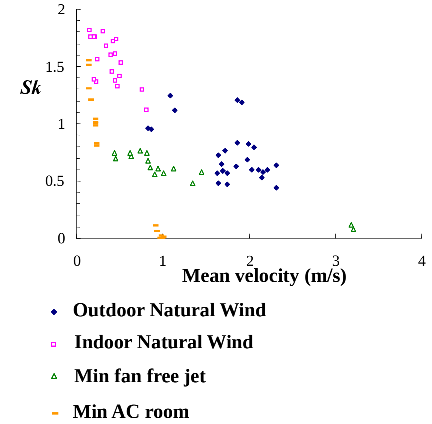



**Fig.5 *Sk* values of natural and mechanical wind[26]**

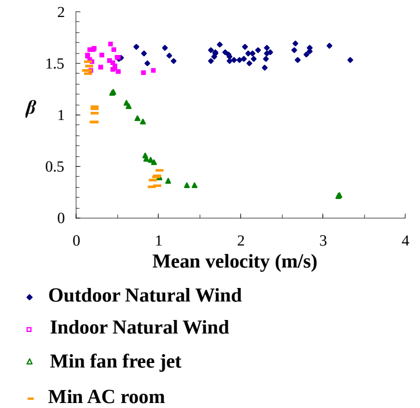



**Fig.6 *β* values of natural and mechanical wind [26]**

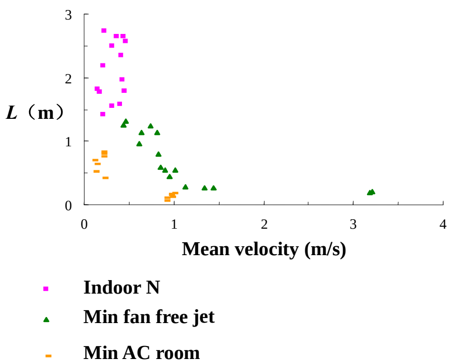



**Fig.7 *L* values of natural and mechanical wind [26]**

Figure 8 shows the change of *e* value of natural wind and mechanical wind with mean velocity. It can be seen that *e* value of natural wind keep constant around 0.32, which indicates that it is *1/f* fluctuations. However , for mechanical wind, the spectral characteristics in low frequency scope are close to white-noise near the air supply opening and those are *1/f* fluctuations only in high frequency (see figure 9 curve 1). Thus e value is smaller and around 0.3. With the diffusion in space, spectral characteristics drift from curve 1 to curve 3, and finally close to the one of natural wind (see figure 9 curve 4). During this process, *e* value increases first and decreases then. When *β* value of mechanical wind is close to the one of natural wind, *e* value decrease to about 0.3 .

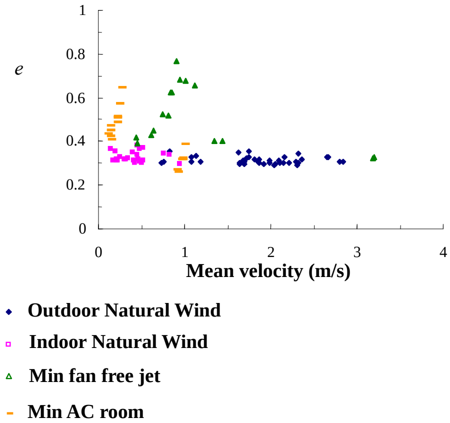



**Fig.8 *e* value of natural and mechanical wind [26]**

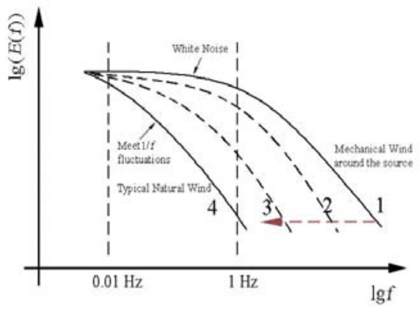



**Fig.9 The spectral characteristic of natural and mechanical wind [26]**

Based on the earlier studies by researchers of Tsinghua University, Ouyang[26] chose and supplemented criterions to distinguish natural and mechanical wind. Those parameters suggested above are independent from each other and relevant to human thermal comfort, and can be used to define fluctuant characteristics of airflow.

3.2 Studies on Shifting Rule of Fluctuant Characteristics

In order to study the shifting rule of mechanical fluctuant characteristics, Jia [13] studied the change of turbulence intensity with distance from the fan outlet and found that turbulence intensity was almost unaffected by the distance.

Meanwhile, Xia [9] found that turbulence intensity varied obviously with distance from the fan outlet through similar experiments. Later, Zhou et al [22]found out from further experiments that there exists a critical distance from the fan outlet, within which turbulence intensity varied obviously with distance and remained constant out of the distance. Dai and Ouyang [23] investigated the shifting rule of fluctuant characteristics of mechanical wind and the results shows that for either centrifugal fan or axial fan, the fluctuant characteristics has a certain variation at the jet distance. At the jet distance, the fluctuant characteristics of mechanical wind would gradually transfer to those of natural wind according to the criteria proposed by Zhu [19].

Above studies found that even though fluctuant characteristics of natural wind were obviously different from those of mechanical wind in many different bulit environments, the fluctuant characteristics of mechanical wind can shift to the ones of natural wind in some conditions.

## 4. SUMMARY

Although the history of the study on dynamic characteristics of airflow is short, some valuable results have been achieved, such as *1/f* fluctuations of natural wind, the differences and connections of fluctuant characteristics between natural and mechanical wind, and the shifting rule of airflow fluctuant characteristics. At the same time, it should be mentioned that many basic theoretic problems still remain unsolved. For instance, are there any other physical parameters to describe the differences of fluctuant characteristics between natural and mechanical wind? How to develop and consummate the machine to simulate the natural wind? And how to integrate the method of CFD and the method of simulating experimentation into the research. All these problems need further study.

## 5. CONCLUSION

The effect of dynamic characteristics on thermal comfort and fluctuant characteristics of fluctuant airflow are both important subjects in built environmental studies. Systematical studies on both subjects are the only way to create dynamic thermal environment by using artificial method according to human comfort, and energy cost can be reduced as well as by avoiding decline of human temperature adjustment function and resistance, in order to bring out a fundamental innovation in air-condition method.

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